Impact and Effect of Formative Feedback Improvement for Dormant Deficiencies in MCAD Education

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Abstract. Considerable improvement in student performance and in learning outcomes has been achieved with an educational intervention previously introduced to a CAD course for mechanical engineering. This intervention was based on the novel dormant deficiency concept and metric, and a software-based feedback agent, among other innovations. This step aimed to address the shortcomings of most software tools and educational interventions for automated grading and assessment of CAD models, such as those currently provided to students in CAD courses. Most approaches are not structured to assess CAD model quality with respect to robustness and alterability, due to their static and exclusive nature, which often leads them to discount CAD model regeneration processes and their impact after alteration. However, it also became evident that students still have difficulties handling and correcting shortcomings and errors in their CAD models regarding certain types of dormant deficiencies. This led to several spin-off projects. One such project aimed at extending and improving the quality, scope, and detail of the feedback generated by the software-based feedback agent. After successful prototyping and usability testing, this improved feedback intervention was provided to all CAD course students. The results and outcomes of that project, together with an empirical study, are reported in this paper.

Keywords: Computer-based feedback provision, student self-assessment, skill and competency development, dormant deficiency, CAD model quality, and robustness.
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1 INTRODUCTION

Providing formative feedback (cf. [18,20,34]) is still a challenge in mechanical engineering CAD (MCAD) education, particularly when it needs to be timely, high-quality, and personalized feedback (see also [3,23,32,38]) to help students with learning and skill development aimed at creating well-designed and robust parametric CAD models, which are central for product or part family development. Tools and methods using automated grading as described, for example, in

[6,8,10,14,19] are limited by their metrics and by their assessment approach. In particular, the metrics they use are of a rather static and exclusive nature, relying heavily on the final outcome. That is to say that they rely upon the completed CAD model, which then has its data structure compared to that of a fixed reference solution. Such approaches are not structured suitably to assess CAD model quality in regard to robustness and alterability. Their static and exclusive nature usually leads them to discount CAD model regeneration processes and their impact after alteration. They are also not sufficiently structured to explicitly support formative self-assessment carried out by students during individual steps of the modeling process as part of their exercise work. This problem arises because the software tools used are unable to assess partially-created CAD models, since they appear to be incomplete according to the metrics and rubrics provided in relation to the exercise specification and the fixed reference solution associated with it. In general, however, those approaches to the automation of CAD model grading are obviously capable of considerably reducing the time required for analyzing and assessing CAD models created by students. However, besides exhibiting the shortcomings outlined above, those approaches are also still quite limited in the type and complexity of CAD model that can be analyzed, and the quality of the feedback that is generated. In particular, examples of recent approaches for technical drawings and 2D CAD files can be found in [8,19,39]. Examples of recent approaches for 3D CAD models and related empirical studies are reported in [4,16,22]. An interesting approach to providing visual feedback for automated CAD model grading using heat maps is reported in [21]. Further discussions on the subject of automated CAD model grading, including a summary of the literature and pointers to gaps in research, can be found in [14].

During continuing improvements to an MCAD course that was restructured by the authors lately, several of these issues have been addressed. In particular, the issue of feedback provision was approached by introducing the dormant deficiency concept and metric. This concept includes 3 types of dormant deficiency (cf. [27,30]) and is aimed at supporting students in acquiring the knowledge and skills development needed to create robust alterable CAD models. This novel concept and classification system comes with a metric which allows for describing and quantifying the impact that errors in feature associativity can have on parametric feature-based CAD models (cf. [26,27,30]). Those errors in associativity, which were introduced during the modeling process due to mistakes in the specification of dependencies between geometric entities, remain dormant until an actual CAD model regeneration is triggered and executed through an alteration.

This paper is structured as follows. First, in section 2, an overview is provided of past and current developments in the restructuring of an MCAD course, along with some background on the novel dormant deficiency concept and metric, aimed at supporting students in acquiring the knowledge and skill development needed to create robust alterable CAD models. Next, in section 3, some discussion is provided, along with a case in point, demonstrating current problems regarding design intent and dissonances between best practices and requirements stemming from actual parametric feature-based CAD model creation. This is followed, in section 4, by a detailed empirical study reporting analysis and results of performance outcome and the effect of improved software-based formative feedback taking into account dormant deficiencies. Finally, in the last section, a brief summary is provided of outcomes achieved so far, and an overview is given of work currently in progress, along with conclusions drawn.

2 BACKGROUND AND SCOPE

Within the recently restructured MCAD course (see overview in Figure 1), various modeling exercises are provided employing a novel teaching approach that systematically utilizes negative knowledge in addition to traditional lectures and tutorials. Each of these modeling exercises addresses a particular learning goal. Outcomes of the exercises, in the form of CAD models created by students, are collected and analyzed to identify shortcomings and errors that usually remain hidden from students due to their limited domain knowledge and expertise. Results are then used as input for formative assessment and feedback. Currently, a series of design and modeling exercises is being administered, with each exercise corresponding to the domain subject taught in the individual course units associated with it. The exercise assignments are designed to begin with a less complex design object and gradually increase in the complexity of the modeling task and the object shape as progress is made in the course and the domain subject being taught.

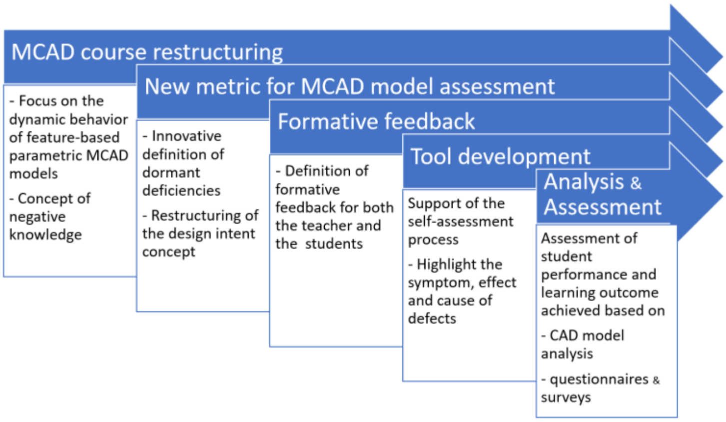


Figure 1: Overview of goals and developments associated with the restructuring of an MCAD course.

The restructuring of the MCAD course consisted of various types of improvement (cf. [24,25,29]), including the development of negative CAD domain knowledge and expertise, and the development of the working knowledge and skills required to create robust alterable parametric CAD models. The latter was approached by introducing the dormant deficiency concept and metric. This concept, outlined below, is aimed at supporting students in acquiring the knowledge and skill development needed to create robust, alterable CAD models. To provide a means for students to see this concept coming alive, as well as having timely, high-quality feedback on this metric applied to the CAD models that they have created in the CAD laboratory and in exercise assignments, a software-based feedback agent was developed and subsequently provided to all MCAD course students. Analysis and evaluation of project outcomes, a survey, and engagement with students during lectures and exercises provided several indications as to where improvements might be required and for the directions in which those might be pursued. One such indication was the need for improvement of the feedback that is generated by the software-based feedback agent. This was addressed with a spin-off project that expands upon previous work (cf. [27]). Results and outcomes of this spin-off project aimed at feedback improvement were investigated within a project follow-up that is described in this paper.

Dormant deficiencies are part of a novel deficiency concept and classification system, with a metric that allows for describing and quantifying the impact that errors in feature associativity can have on parametric feature-based CAD models (cf. [30]). Those errors in associativity, which were introduced during the modeling process due to mistakes in the specification of dependencies between geometric entities, remain dormant until an actual CAD model regeneration is triggered and executed through an alteration. In this context, the outcome in regard to deficiencies is related to different error situations, upon which dormant deficiencies are classified. For example, type I dormant deficiencies relate to faults in status. The effect of this type of deficiency is that a model change leads to features being either regenerated with unpredictable results or not regenerated at all. The main symptom of a type I dormant deficiency which has been activated is a change in the feature status. The regenerated CAD model contains deficient features, which are labeled with a warning or failed status in the feature history tree. Type II dormant deficiencies relate to faults in shape, and the effect of this type of deficiency is that a regenerated CAD model does not contain any features labeled with a warning or failed status, but the shapes of features are incoherent or even destroyed completely. An example of this is where a cutout feature is partially moved outside the geometric boundary of the target body. The main symptom of a type II dormant deficiency that has been activated is a change in the local topology of the features affected by this deficiency.

3 SOME CONSIDERATIONS ON DORMANT DEFICIENCY, DESIGN INTENT, AND CASES OF INCONGRUITY BETWEEN BEST PRACTICES AND CAD MODELING REQUIREMENTS

3.1 Design Intent and Dissonance between Best Practices and CAD Model Creation

Geometry forms the foundation for all CAD designs, while providing a framework for creating digital models and manipulating twins. Parametric feature-based CAD systems allow users to define relationships and constraints between geometric elements. This enables them to modify designs easily and explore different design iterations without having to recreate the entire CAD model from scratch. Here, geometric constraints ensure the integrity and robustness, and thus the quality, of the CAD models created. The constraints are also a crucial precondition for the regeneration of CAD models after parameters have been altered, so that few, or ideally zero, failures and deficiencies are encountered. Constraints are also used to support capturing the design intent of a devised solution along with the right dimensions, features, and details of work geometry.

However, this design intent, as generally used within the CAD context (cf. discussions in [7]), differs from the design intent as used within an engineering context. The central difference becomes visible in a functional or structural dissonance of approach, and implementation of the intent through CAD model geometry and related details such as feature types, modeling history, constraints, and sketches, as discussed in this paper. Therefore, to avoid confusion, the authors distinguish between what is referred to as the *modeling design intent* – usually simply called design intent – and what is referred to as the *engineering design intent*. The modeling design intent relates more to CAD system limitations and the modeling process itself, so that the geometry of a CAD model can easily be modified, with changes appearing in a regenerated CAD model in a predictable and coherent manner. The engineering design intent, which is the ultimate goal of the design of a part or component represented by the geometry of the CAD model, relates more to the creation of a geometry that defines shapes that are suitable for performing or supporting basic engineering functionalities, like fixing, connecting, guiding, enclosing or housing.

To achieve the creation of robust and high-quality CAD models that are manageable, best practices and guidelines for parametric feature-based modeling should be followed, as discussed, for example, in [1,2,5,9,13,15,28] – and see also guidelines on assisting in the creation of high-quality CAD models in [36]. Those guidelines include well-known principles such as renaming features in the model tree, fully defining and constraining profiles and sketches, not overloading sketches so that they remain manageable and transparent, staying clear of placing fillets and chamfers in sketches, and avoiding unnecessary features.

Generally, these best practices and guidelines support the creation of high-quality, robust CAD models. However, sometimes they may create dissonances with respect to the need to implement a modeling sequence that will respect the rationale behind the engineering design of a part or component subject to a design solution. In such cases, the modeling outcome may result in a CAD model that is deemed robust and well-made from the modeling–design intent point of view, but, at the same time, is deemed weak in capturing the actual engineering design intent. The following example, using a small selection of principles taken from best practices and guidelines commonly taught in educational and training settings, and as used by numerous designers and engineers employing parametric feature-based CAD systems in commercial and industrial praxis, may help illustrate this situation.

Consider the following selection of principles.

- **Create volumes first and cutouts next**: This makes the modeling sequence easier to interpret. It also limits the risk of introducing so-called *undo features*, which are sometimes required to recover from situations where the model shape has been impaired. Typical cases are, for example, cutouts or depression features that are partially occluded or covered by extrusion features.

- **Keep profiles as simple as possible**: This supports the defining of fully constrained profiles. It also helps manage both constraints used to define a profile and constraints used to relate features to each other.

- **Keep features independent**: This improves the readability of the CAD model structure and assists in understanding the effect of a change and its impact upon CAD model regeneration. Keeping features independent also makes the definition and generation of CAD model alternatives easier, especially in cases where model regeneration is driven by suppressing some features.

Now, taking into account the distinction between engineering design intent and modeling design intent with respect to creating a robust, sound, high-quality CAD model, some shortcomings and dissonances might be encountered as follows.

- **Create volumes first and cutouts next**: A shape element that allows for designing engineering functionality, such as fixing, guiding, or providing passage, is a kind of depression, and its positioning is usually a design constraint. For this reason, the size and location should be managed with appropriate dimensions, such as the center-to-center distance of fixing holes or the position of a slot. The volume around such features is then a consequence of the size and position of such cutout or depression features. Therefore, the related engineering design rationale is comprised of two consecutive steps, namely to dimension and position these depressions first and to define the surrounding volume next.

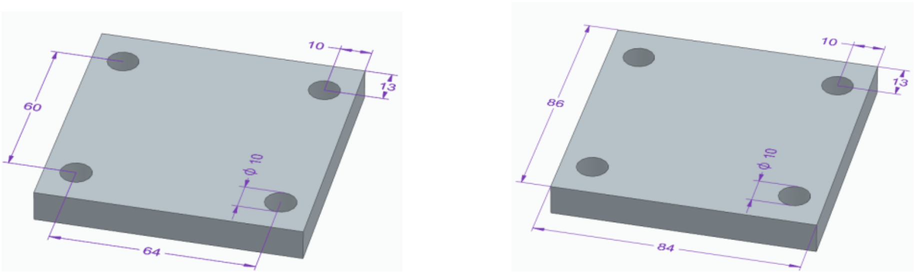
- **Keep profiles as simple as possible**: This principle represents a means of overcoming the previously mentioned issues of managing profiles and constraints, while, in general, introducing functional reference elements, that is to say, using sketches. However, when used for such purposes, sketches can easily become complex due to the need to relate several elements, such as geometric entities and even features.

- **Keep features independent**: Although this principle is, in general, good advice, especially in cases where the suppression of some features should not have an unpredictable or adverse impact on the CAD model after regeneration, there are situations where the dependency between features is part of the engineering design rationale, such as in the case of volumes that are surrounding or enclosing depressions.

3.2 A Case in Point

To illustrate the previously discussed incongruency between best practices and actual modeling requirements, along with some possible workarounds, a case in point is given in the following. Take the design of a simple fixture part consisting of a rectangular base plate with 4 fixing holes as shown in Figure 2(a). Here, the diameters of the holes and the axis-to-axis reciprocal position are usually design constraints, because they define the mounting interface of the component.

Notice that, from a design point of view, the two dimensioning solutions shown in Figure 2(a) and Figure 2(b) are not equivalent, due to issues related to tolerances. In particular, in the case shown in Figure 2(a), the axis-to-axis dimension is explicit; thus, the dimensions of the base are a consequence of the positions of the holes. In the case shown in Figure 2(b), the explicit dimensioning is applied to the base. Thus, the axis-to-axis dimensions of the fixing holes are a consequence, and it is important to note that those axis-to-axis dimensions are no longer explicitly available to the designer should adjustments to the model be required.

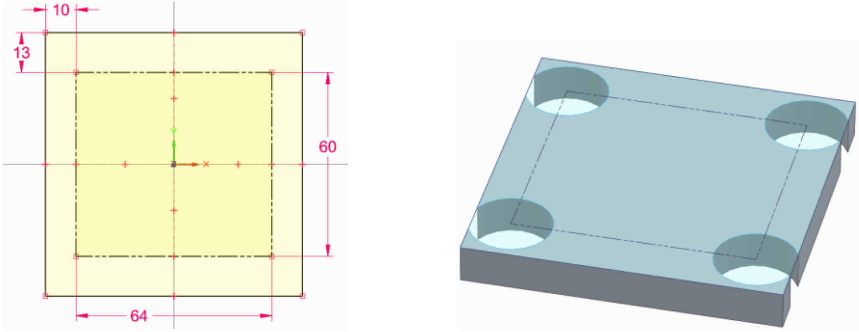


(a) (b)

Figure 2: Example of dimensioning solutions for a simple fixture part model. From left to right: (a) explicit axis-to-axis dimensioning of the fixing holes, (b) explicit dimensioning of the base.

Moreover, in the case shown in Figure 2(a), a parametric feature-based CAD model can be created only by modeling the fixing holes first and the base next. Here, the user has to face both a violation of best practices regarding the creation of volumes first and cutouts next, and the insurmountable task of beginning the modeling with a depression feature, as currently available CAD systems do not allow the creation of any depressions in cases where a volume is not already present in the CAD model.

However, workarounds are available to cope with such CAD system shortcomings and conceptual modeling issues. In the case discussed, an alternative approach is based on the use of a sketch (cf. Figure 3(a)), which can be created at any time during modeling, even before any volume – relating to the CAD model geometry – has been created.

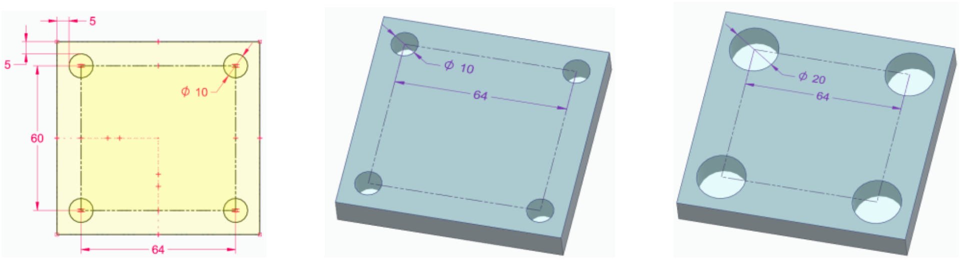


(a) (b)

Figure 3: Example of a sketch-based dimensioning solution for a simple fixture part model. From left to right: (a) initial sketch with dimensioning, (b) regenerated CAD model after the fixing hole diameter is increased.

However, this approach alone does not provide a stable solution to the problem outlined. For example, suppose the fixing hole diameter is increased. In that case, the model can become inconsistent to the point of being deficient (cf. Figure 3(b)), as the distance between the fixing holes and the base boundary decreases. Note that, due to a critical modeling situation, this would lead not only to a type II dormant deficiency, but also to an issue from the engineering design point of view.

To overcome the issues outlined, the profile of the fixing holes should be added to the sketch. Additionally, the dimensioning should be changed in a manner that ensures that the profile of the base is related to the outer boundary of the fixing holes. However, those amendments result in a more complex CAD model profile and a quite cryptic dimensioning, as shown in Figure 4(a).



(a) (b) (c)

Figure 4: Example of a more complex sketch-based dimensioning solution for a simple fixture part model. From left to right: (a) initial sketch with dimensioning and additional profiles, (b) generated CAD model based on the initial sketch and dimensioning, (c) regenerated CAD model after the hole diameter is increased.

Notice that even the location of the axis of the holes in respect to the base boundary is no longer represented explicitly. This presents another dissonance between best practices, which suggest that CAD model profiles should be kept as simple as possible, and the requirements faced during the design with actual CAD systems. Moreover, many currently available CAD systems do not allow the use of a profile to define a hole feature. In those cases, a generic extruded cutout must be used instead. This system restriction, however, results in a severe drawback, because all the functionality related to a hole feature, such as standard diameters, and the adding of chamfers and threads, is lost.

A different and more elegant and robust method of approaching the issue outlined above is related to the use of equations, through which relationships among variables of the CAD model can be expressed. In the example shown in Figure 4(b) and Figure 4(c), first the base can be modeled by selecting the profile from the sketch. Second, hole features can be added to the CAD model by selecting appropriate properties such as hole diameters. Subsequently, positioning of the holes can be carried out by taking advantage of the sketch layout. Then the variable table of the CAD model can be used to define the equation that will relate the fixing hole diameter to the outer dimension of the base, taking into account a value for the minimum distance required from the fixing holes to the base boundary. Although this approach represents an elegant and robust solution to preserve both the engineering design intent and the modeling design intent, some 'hidden' relationships have been set up between the holes and the base, and that represents a dissonance in respect to best practices, which advocate the avoidance of unnecessary relationships between modeling features.

4 EMPIRICAL STUDY

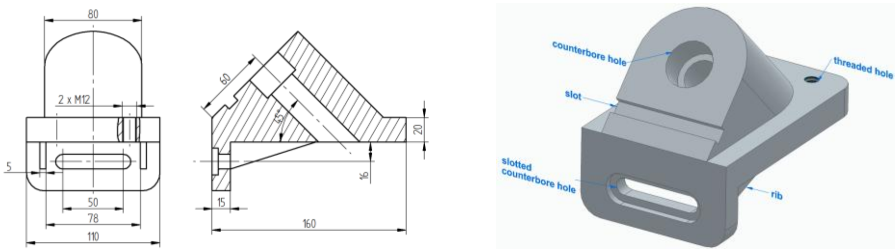
4.1 Research Design, Data Sets, and Method

The objective of the second step of this project follow-up study was to determine and verify qualitatively and quantitatively the impact of the improved educational intervention. Outcomes of that are then used to identify areas for improvement in a manner that allows for adjustment and refinement so as to ensure that, in the long run, this educational intervention will be able to sustain its quality and provide substantial benefits while retaining effectiveness and efficiency. In particular, the study presented in this paper addressed the following research questions:

RQ1: What were the efficacy and progress of the educational intervention in the form of extended and improved software tool-based formative feedback in the context of creating robust parametric feature-based CAD models?

RQ2: Which areas and directions for improvement can be identified for adjustment and refinement to ensure that, in the long run, this educational intervention will be able to sustain its quality and provide substantial benefits?

The study was conducted through a quasi-experimental research design with two sets (control / experimental) of student-created CAD models. The control set consisted of CAD models that had been submitted by students who did not make use of the improved software-based feedback agent. The experimental set consisted of CAD models submitted by students who did use the improved software-based feedback agent. All CAD models used in the study were created as part of concrete exercise assignments and CAD laboratory activities (see Figure 5), which are components of an actual CAD course for mechanical engineering at the institution where the authors operate. The improved software-based feedback agent features a technical architecture that leverages API-based functionality provided by commercially available CAD systems to support a modular and highly cohesive system architecture. Within the current implementation, the modeling environment deploys a commercially available parametric feature-based solid modeling system, namely *SolidEdge* from Siemens Digital Industries Software (for more details see [26,31, 35]). The CAD course is designed for mechanical engineering students in their second year of undergraduate studies.



(a) (b)

Figure 5: Example of an actual CAD course exercise assignment. From left to right: (a) outline and overall dimensions of the CAD model, (b) rendered shape of the CAD model.

After initial model validity and data integrity checks, a total of N = 80 (control n = 19 / experimental n = 61) student-created CAD models were deployed in the observational study. All CAD models that were deployed in the study were analyzed and assessed individually by the authors. Results obtained were then cross-checked to verify the accuracy, correctness, and integrity of the analysis and its outcome.

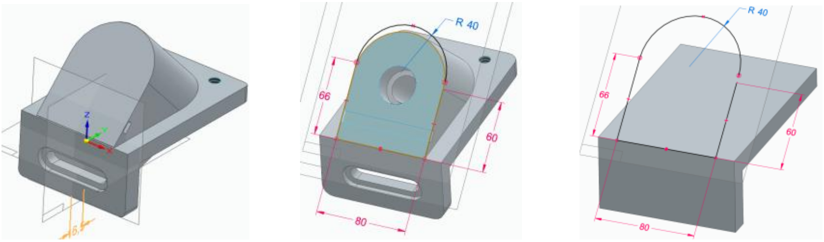
4.2 Analysis and Results

4.2.1 Performance outcome and effect of improved feedback

Considerable improvement in student performance and in learning outcomes could be achieved through extension and improvement of the agent-based formative feedback. Analysis and assessment of the feature-based CAD models created by students using the improved agent-based formative feedback throughout a series of design and modeling exercises showed that the proportion of CAD models that contained dormant deficiencies decreased significantly compared with the proportion of models by students who did not use it. For the CAD model set discussed in this paper (see again Figure 5), this proportion was reduced from 57.89% to 27.87%. The calculated individual odds yielded an odds ratio OR = 3.559. Using the common conversion method described in [11] – which relates to a standardized mean difference statistic (cf. [17,33]) – this translates into a standard effect size measure (cf. [12]) expressed as Cohen's d = 0.701. The odds ratio has an approximate 95% confidence interval CI = [1.222, 10.365] with the approximate standard error of the log odds ratio $SE(\ln(OR)) = 0.5453$. Thus, the overall odds that a CAD model would contain a dormant deficiency were a little above 3.5 times as high for a CAD model that had been created by a student without the improved feedback intervention as for a CAD model that had been created by a student with the improved feedback intervention. As the confidence interval does not include an odds ratio of 1, the result is statistically significant at the 5% level. This outcome is further confirmed through the chi-square test ($df = 1$, $\chi^2 = 5.7412$, $p = 1.657e\text{-}2$), which also yields a statistically significant relationship at the 5% level between the presence or absence of dormant deficiencies and CAD models that were created without using any feedback intervention and those that were created with improved feedback intervention. In the case of CAD models that contained only type I dormant deficiencies, the calculated individual odds yielded an odds ratio $OR = 5.347$, which translates into a standard effect size measure expressed as Cohen's $d = 0.926$. This odds ratio has a 95% confidence interval $CI = [1.522, 18.787]$ with the approximate standard error of the log odds ratio $SE(\ln(OR)) = 0.6411$. Results computed for the chi-square test ($df = 1$, $\chi^2 = 7.7638$, $p = 5.332e\text{-}3$) also indicate a statistically significant relationship at the 5% level between the presence or absence of type I dormant deficiencies and student-created CAD models that were produced without using any feedback intervention and those that were produced with improved feedback intervention.

4.2.2 Detailed CAD model analysis

Detailed analysis of the student-created CAD models that contained dormant deficiencies revealed the nature and structure of several issues related to those deficiencies. In cases of CAD models with type I dormant deficiency, the most common issues, that is the causes of the deficiencies, were related to the use of constraints, and mistakes in basic dimensioning. Using either more or fewer constraints than necessary resulted in over- or under-constraining, either of which is prone to produce inconsistencies when CAD models are altered and regenerated, as is the use of constraints that are inadequate or incorrect. These causes of type I dormant deficiency had various detrimental effects on the CAD models, and were accompanied by a variety of symptoms. Some CAD models with type I dormant deficiency were found to contain features which had an incorrectly generated shape, and some features were not generated at all after CAD model regeneration. These problems were found to be related to issues such as non-manifold geometry, cracks in otherwise closed profiles, and a loss of reference to geometric entities. A typical example of the last-mentioned problem is shown in Figure 6(a).



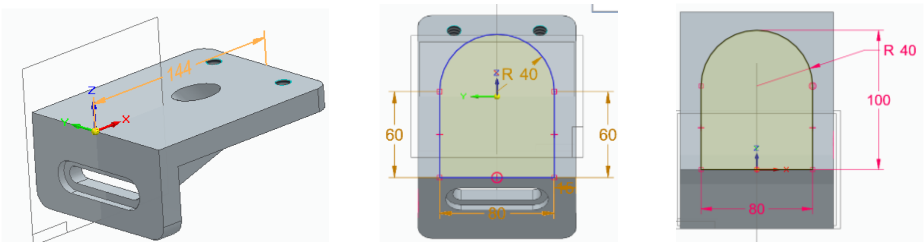
(a) (b) (c)

Figure 6: Examples of CAD models displaying the effect and impact of type I dormant deficiencies after parameter changes and model regeneration. From left to right: (a) regenerated CAD model where some features affected by alterations are not regenerated at all due to a lost reference to a geometric entity, (b) CAD model with some of its parameter values altered, before regeneration, (c) CAD model with some of its parameter values altered, resulting in a gap in the profile.

Here, the inclined plane of the long semi-circular mounting flange is constrained incorrectly in regard to the upper frontal edge of the L-shaped base flange (see again Figure 6(a)). Hence, after

CAD model alteration, the features that should be located on this plane have lost their reference to it, and consequently are not regenerated correctly.

A typical example of compromised closure of profiles is shown in Figure 6(c). Here the profile of the long semi-circular flange is constrained incorrectly. When one of its dimensions is increased (cf. Figure 6(b)), the profile becomes open. After CAD model regeneration this results in a flawed shape for the long semi-circular flange, because it has been regenerated based on the parameter value settings prior to alteration, thus excluding any changes that have been made.

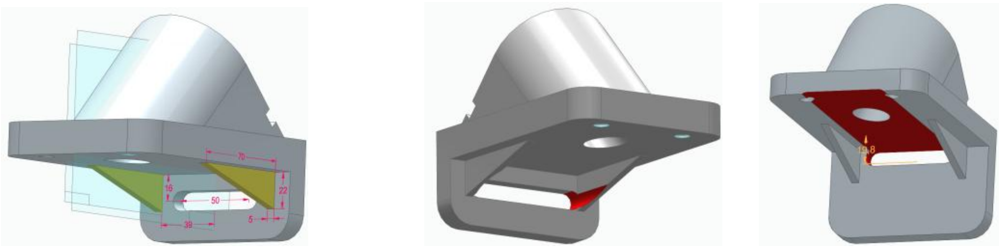


(a) (b) (c)

Figure 7: Examples of CAD models displaying the effect and impact of type I dormant deficiencies after parameter changes and model regeneration. From left to right: (a) regenerated CAD model where some features affected by alterations are not regenerated, (b) CAD model with one of its profiles and defining parameter sets related to the long semi-circular mounting flange, before alteration, (c) CAD model with one of its profiles and defining parameter sets related to the long semi-circular mounting flange, after alteration.

An example typical of issues related to inadequate basic dimensioning is shown in Figure 7(a). Here, CAD model alteration aimed at reducing the overall length of the L-shaped base flange can quickly reach parameter values that cause the semi-circular mounting flange to exceed the boundary of the L-shaped base. This results in a CAD model regeneration where the shape of the semi-circular flange is no longer created. A representative example of cases of inadequate constraints is shown in Figure 7(b). If a dimension value is altered, the set of constraints becomes inconsistent (cf. Figure 7(c)), resulting in incorrect or missing feature shapes during CAD model regeneration. There were also cases of incorrect constraints that led to non-manifold geometry in feature shapes, and thus to features not being generated during CAD model regeneration. This was related to positioning errors involving the L-shaped base flange, the two stiffening ribs, and the slotted counterbore hole. Note that this hole may also be known as the trench hole or the counterbore slot, but it will be referred to in this paper simply as the slot hole. In these situations, modifications to the slot hole length and/or the width of the L-shaped base flange may result in a tangency between the curved vertical slot hole ends and parts of the vertical boundary of the ribs, thus creating non-manifold geometry.

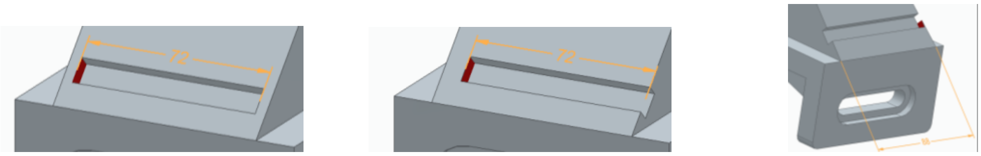
In cases of CAD models with type II dormant deficiency, the most common issues were related to a lack of understanding of how to use the command correctly for creating properly positioned slot features and to the use of constraints. However, the latter was of a nature different from the cases of CAD models with type I dormant deficiency. Here, over- or under-constraining was not an issue, but using constraints correctly – mostly within profile definitions – to properly define relationships between geometric entities at the inter- or intra-feature level was a problem. A typical example of the former, encountered during analysis, is shown in Figure 8. Here, the slot feature was positioned in a manner so as to remain symmetric in respect to a referenced symmetry plane, as shown in Figure 8(a). The first rib feature was created by defining its profile on a plane parallel to the referenced plane, while positioned at a finite distance from it. Taking advantage of these symmetric conditions, the second rib was created using a mirror copy feature. However, if the inter-feature relationship between the length of the slot feature and the position of the first rib feature is not correctly defined, critical situations lead to the introduction of dormant deficiencies. The resulting effect and impact are shown in Figure 8(b). A similar case, but related to issues affecting the alteration of slot feature parameter values in a vertical direction, is shown in Figure 8(c).



(a) (b) (c)

Figure 8: Examples of CAD models displaying the effect and impact of type II dormant deficiencies after parameter changes and model regeneration. From left to right: (a) CAD model and some of its parameter value settings with type II dormant deficiency, before regeneration, (b) regenerated CAD model with type II dormant deficiency containing visible deficiencies in features affected, after alteration of slot feature parameter values in horizontal direction, (c) regenerated CAD model with type II dormant deficiency containing visible deficiencies in features affected, after alteration of slot feature parameter values in vertical direction.

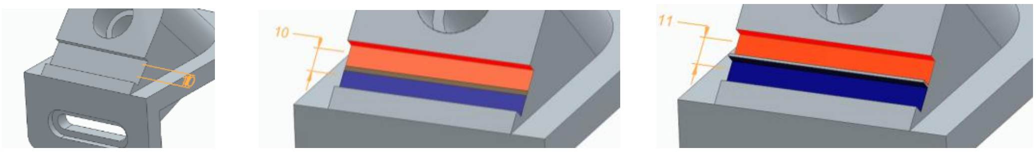
Another type II dormant deficiency caused by errors in inter-feature relationships is related to the use of a fixed slot length dimension, ignoring the requirement to constrain this slot length to the boundary of the long semi-circular mounting flange. In cases where this deficiency was present, an increase in the slot length or a decrease in the mounting flange width resulted in an incoherent shape. The slot either became a pocket or was closed on one side, as shown in Figure 9(a) and Figure 9(b), respectively. A case with a similar mistake that was immediately detected by the feedback agent had additional shortcomings in the profile definition of the semi-circular mounting flange. This caused a loss of parallelism in its two lateral flange segments. This deficiency led additionally to a very small slot shape defect, as shown in Figure 9(c).



(a) (b) (c)

Figure 9: Examples of CAD models displaying the effect and impact of type II dormant deficiencies after parameter changes and model regeneration. From left to right: (a) enlarged section of a regenerated CAD model containing a pocket after alterations to slot feature parameter values, (b) enlarged section of a regenerated CAD model containing deficiencies in features affected by alterations to slot feature parameter values, (c) enlarged section of a regenerated CAD model containing deficiencies in features affected by decreasing the semi-circular mounting flange width.

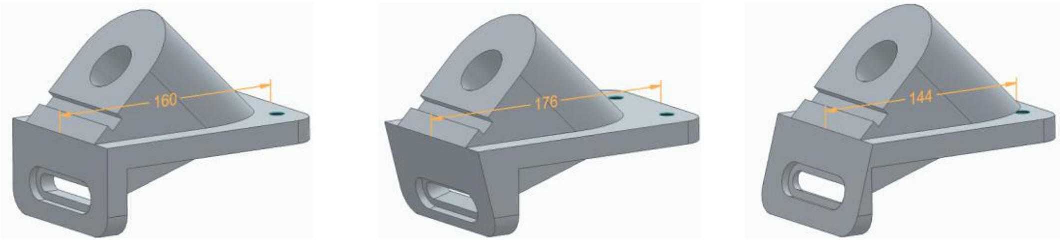
Some errors were committed due to insufficient understanding of the command for creating slot features. These errors related to the specification of the slot position using a closed profile instead of a single segment. This mistake resulted in the creation of two slots at once. However, the symptoms of this type II dormant deficiency are usually not visible to the naked eye of the user, even after CAD model regeneration, unless slot parameter values increase beyond a certain threshold (cf. Figure 10(a)), as shown in Figure 10(b) and Figure 10(c).



(a) (b) (c)

Figure 10: Examples of CAD models displaying the effect and impact of type II dormant deficiency within a slot feature after parameter changes and model regeneration. From left to right: (a) enlarged section of a CAD model and some of its parameter value settings, before regeneration, (b) enlarged section of a CAD model with settings of slot feature parameter values, (c) enlarged section of a regenerated CAD model containing visible deficiencies in features affected, after alteration of slot feature parameter values.

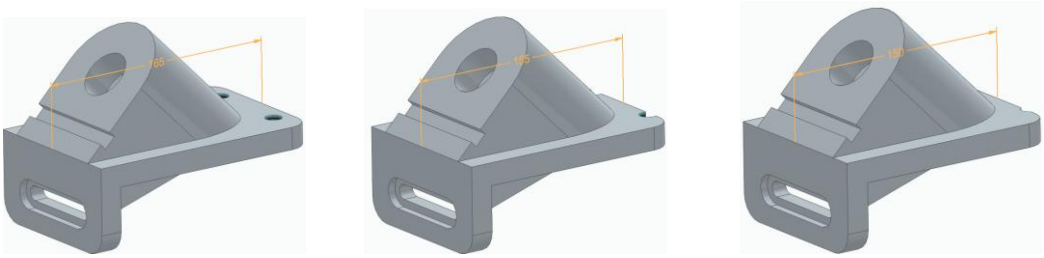
Incorrect constraints in otherwise fully constrained profiles were also found in features used to create the L-shaped base flange of the mounting support. Here the L-shaped base flange suffered shape incoherency when its major length parameter value (cf. Figure 11(a)) was altered as shown in Figure 11(b) and Figure 11(c).



(a) (b) (c)

Figure 11: Examples of CAD models displaying the effect and impact of type II dormant deficiencies after parameter changes and model regeneration. From left to right: (a) CAD model and some of its parameter value settings with type II dormant deficiency, before regeneration, (b) regenerated CAD model with type II dormant deficiency containing visible shape incoherency, after increasing the major length parameter value of the L-shaped base flange, (c) regenerated CAD model with type II dormant deficiency containing visible shape incoherency, after decreasing the major length parameter value of the L-shaped base flange.

Figure 12 shows a typical case of type II dormant deficiency related to errors in the inter-feature relationship between a pair of fixing holes and elements of the L-shaped base flange. Here, parameter value alterations that reduce the length of the L-shape base flange result in shape incoherency, as shown in Figure 12(b) and Figure 12(c).



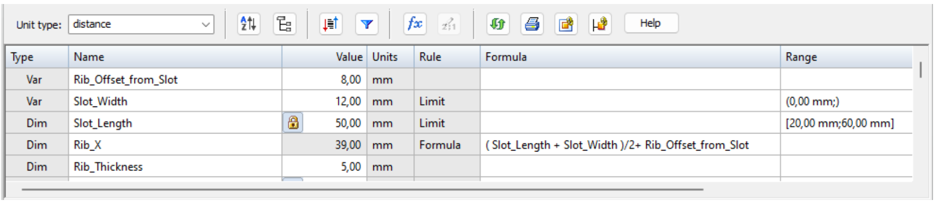
(a) (b) (c)

Figure 12: Examples of CAD models displaying the effect and impact of type II dormant deficiencies after parameter changes and model regeneration. From left to right: (a) CAD model and some of its parameter value settings with type II dormant deficiency, before regeneration, (b) regenerated CAD model with type II dormant deficiency containing visible deficiencies in features affected by decreasing the major length parameter value of the L-shaped base flange, (c) regenerated CAD model with type II dormant deficiency containing visible deficiencies in features affected by further decreasing the major length parameter value of the L-shaped base flange.

4.3 Discussion

In reference to research question RQ1 concerning the outcome and performance of students in relation to the quality and robustness of the CAD models that were created after the introduction of extended and improved software tool-based formative feedback, a significant improvement was observed. This was reflected in, among other factors, a significant decrease in dormant deficiencies and a considerable increase in the effect size of this educational intervention. Based on observations made during the CAD course, this level of learning outcome and skill development appeared to have been achieved faster by students who used the improved feedback intervention. This suggests that the improved feedback intervention engages students in more effective actions that help improve existing behavior, knowledge, and skills, which is the basic goal of any learning experience.

Regarding research question RQ2, results from the detailed analysis, some of which have been outlined earlier, indicate that defining constraints properly – especially within the definition of profiles and geometric properties – to avoid type II dormant deficiencies is still problematic for students. On the other hand, many of the critical situations identified could be avoided by reducing the sometimes-unnecessary complexity of constraints as used by students. In many cases, this can be achieved by using formulae. However, to enable the proper use of formulae, CAD models should be reasonably well designed, in a manner such that the features, profiles, and constraints used for creating the CAD model respect best practices and engineering design intent to the level deemed reasonable for novices within an educational setting, as discussed elsewhere in this paper. To illustrate this with a concrete example, consider again the case shown in Figure 8(a) and Figure 8(b). In this case, if the relationship between the slot feature length and the position of the first rib feature is not defined, a critical situation may arise leading to a type II dormant deficiency. This is due to feature shape intersections (see again Figure 8(b)). However, taking advantage of the set of variables created by any commercially available parametric feature-based CAD system, a distance variable can be applied to define the proper rib location within the CAD model. This can be achieved in a non-complex and straightforward manner by using a formula taking into account the length and width of the slot and the offset of the ribs from the slot. In the example discussed, variables created by the CAD system and inserted into the variables table for the feature, along with the feature dimensions (cf. Figure 13 and Figure 15(a)), are as follows: the length and width of the slot (renamed *Slot_Length* and *Slot_Width*), and the distance between the rib plane and the symmetry plane (renamed *Rib_X*).



Type	Name	Value	Units	Rule	Formula	Range
Var	Rib_Offset_from_Slot	8,00	mm			
Var	Slot_Width	12,00	mm	Limit		(0,00 mm;)
Dim	Slot_Length	50,00	mm	Limit		[20,00 mm;60,00 mm]
Dim	Rib_X	39,00	mm	Formula	(Slot_Length + Slot_Width)/2+ Rib_Offset_from_Slot	
Dim	Rib_Thickness	5,00	mm			

Figure 13: Example of CAD model parameter value settings and a formula for computing the distance between the rib plane and the symmetry plane.

A user-defined variable can also be created to set the offset value of the rib from the slot (see *Rib_Offset_from_Slot* in Figure 13). To ensure that the rib features will be positioned correctly in respect to the slot hole at a distance equal to the required offset, a formula can be generated. This formula then defines how to compute the variable that represents the rib location distance – the distance between the rib plane and the symmetry plane – as shown in Equation (1).

$$Rib\_X = (Slot\_Length + Slot\_Width)/2 + Rib\_Offset\_from\_Slot \quad (1)$$

Unit type: distance

Type	Name	Value	Units	Rule	Formula	Range
Var	Rib_Offset_from_Slot	8,00	mm			
Var	Slot_Width	12,00	mm	Limit		(0,00 mm;)
Dim	Slot_Length	50,00	mm	Formula	(Rib_X - Rib_Offset_from_Slot - Slot_Width /2)*2	
Dim	Rib_X	39,00	mm			
Dim	Rib_Thickness	5,00	mm			

Figure 14: Example of CAD model parameter value settings and a formula for computing the length of the slot feature.

The formula in Equation (1) is used in a scenario where the slot length is the main design constraint, but other scenarios can be considered as well. For example, if the main design constraint is the distance between the two ribs while keeping the slot hole positioned between the two ribs, another formula can be derived to compute the slot hole length, as shown in Equation (2) and Figure 14.

$$Slot\_Length = (Rib\_X - Rib\_Offset\_from\_Slot - Slot\_Width/2)*2 \quad (2)$$

(a) (b)

Figure 15: Examples of CAD model parameter value settings. From left to right: (a) CAD model and some of its parameter value settings, (b) CAD model with a warning issued due to a parameter value exceeding its specified value range.

Note that the user can also set a range of valid variable values instead of a fixed value. For example, in the first variable table shown in Figure 13, the slot length has been set to remain within a range from 20 to 60. If a value is assigned that is out of this range, the system will stop the input, and a warning will be issued through the CAD system interface as shown in Figure 15(b).

The issues discussed above, in particular in regard to research question RQ2, and the difficulties of students who still seem to struggle with defining constraints properly in order to avoid type II dormant deficiencies, led the authors to consider modifications to the CAD course by adjusting parts of the lectures and the CAD laboratory exercises to increase the focus on both the creation of proper less-complex constraints and the use of formulae.

5 CONCLUSIONS AND FUTURE WORK

The results obtained from the second step of this project follow-up provide tangible evidence that the extension and improvement of agent-based formative feedback has indeed led to improvements in both the learning experience and student performance. This was reflected in a considerable reduction in dormant deficiencies in student-created CAD models and a significantly increased effect size of this feedback intervention, among other factors. Here, advancing learning experiences and skill development not only enabled students to create CAD models that were more robust and of better quality, but also reduced the learning time while accelerating progress in student performance. This is due in part to this educational intervention explicitly supporting self-assessment and the self-adjustment efforts of students. These results also indicate not only that this educational intervention is able to sustain its quality and provide substantial benefits while still retaining effectiveness and efficiency, but also that it provides a supporting foundation for exploring innovative means aimed at improving modern MCAD education, such as novel key metrics for indicating success in achieving a desired learning outcome.

Guided by the results obtained through the second step of this project follow-up, as outlined in this paper, and by the insight gained for advancing both the CAD course outcome and the student learning experience, the following measures are currently being designed with the aim of implementation for the next academic year. First, the MCAD course will be adjusted by fine-tuning some parts of the lectures, some CAD laboratory exercises, and course assignments. This will include the more prominent use of formulae and a deeper focus on the role of correctly and fully constrained profiles. Second, more lecture time will be dedicated to the relationships that exist among best practices, the creation and use of well-structured profiles, and dormant deficiencies, especially in regard to their impact on the quality and robustness of CAD models. Third, adjustments will be made to some of the questions on the survey that is conducted by the authors every academic year in parallel with the MCAD course. The survey aims to elicit feedback from students on how they perceive the adjustments that have been made to the course and whether those adjustments have improved the learning experience.

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